Strong interactions: From methods to structures*

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Dedicated to the memory of our friend and colleague Klaus Goeke

ABSTRACT

These are the proceedings of the workshop on "Strong interactions: From methods to structures" held at the Physikzentrum Bad Honnef of the Deutsche Physikalische Gesellschaft, Bad Honnef, Germany from February 12 to 16, 2011. The workshop concentrated on physics of cold atoms, chiral perturbation theory for mesons and baryons, chiral dynamics in few-baryon systems and effective field theories for systems with heavy quarks. Included are a short contribution per talk.

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1 Introduction

Effective field theory techniques have become widely adopted in various fields of theoretical atomic, nuclear and particle physics. The main goal of this workshop was bringing together people using this methodology for studying different facets of strongly interacting matter to present the ongoing developments in various fields and foster discussions and exchange of knowledge. More specifically, the workshop focused on cold-atom physics, chiral perturbation theory and its extensions, nuclear effective field theory and heavy quark physics. Some recent developments in lattice QCD have also been discussed in several talks.

This meeting followed the series of workshops in Ringberg (Germany), 1988, Dobogókö (Hungary), 1991, Karrebæksminde (Denmark), 1993, Trento (Italy), 1996 and Bad Honnef (Germany), 1998, 2001, 2004 and 2006. All these workshops shared similar features, about 50 participants, a fairly large amount of time devoted to discussions rather than presentations and an intimate environment with lots of discussion opportunities.

This meeting took place in February 2011 in the Physikzentrum Bad Honnef in Bad Honnef, Germany, and the financial support provided by the WE–Heraeus–Stiftung allowed us to cover the local expenses for all participants and to support the travel of a fair amount of participants. The WE-Heraeus foundation also provided the administrative support for the workshop in the person of the able secretary Mrs. Elisabeth Nowotka. We extend our sincere gratitude to the WE-Heraeus Stiftung for the support and to Mrs. Nowotka for the precious help in the organization. We would also like to thank the staff of the Physikzentrum for the excellent service given to us during the workshop and last but not least the participants for making this an exciting and lively meeting.

The meeting had 72 participants whose names, institutes and email addresses are listed below. 47 of them presented results in talks of 35 minutes in length. A short description of their contents and a list of the most relevant references can be found below. As in the previous workshops we felt that such mini-proceedings represent a more appropriate framework than full-fledged proceedings. Most results are or will soon be published and available on the archive, so this way we can achieve speedy publication and avoid duplication of results in the archive.

Below follows first the program, then the list of participants followed by the abstracts of (most of) the talks which can also be obtained from the workshop website

`http://www.tp2.ruhr-uni-bochum.de/forschung/vortraege/workshops/bh11/`

N. Brambilla, E. Epelbaum, H.-W. Hammer and U.-G. Meißner

2 Program

Saturday, February 12th 2011

14:20	Evgeny Epelbaum (Bochum)	Introductory Remarks

Early Afternoon Session

Chair: H.-W. Hammer		**Cold Atoms I**
14:30	Matt Wingate (Cambridge)	Monte Carlo computations for Fermi gases
15:05	Lucas Platter (Chalmers)	How a few affect many
15:40	Doerte Blume (Pullman)	Universal features of weakly and strongly interacting few-body systems
16:15		*Coffee*

Late Afternoon Session

Chair: H.-W. Hammer		**Cold Atoms II**
17:00	Joe Carlson (LANL)	Recent progress in simulations of cold atoms
17:35	Mike Birse (Manchester)	Functional RG for few-body systems
18:10	Stefan Flörchinger (CERN)	Functional renormalization and ultracold quantum gases
18:45		*End of Session*
19:00		*Dinner*

Sunday, February 13th, 2011

Early Morning Session

Chair: H.-W. Hammer		**Chiral Perturbation Theory I**
09:00	Hans Bijnens (Lund)	CHPT in new surroundings
09:35	Andre Walker-Loud (Berkeley)	Computing nucleon magnetic moments and electric polarizabilities with lattice QCD in background electric fields
10:10	Sebastien Descotes-Genon (Paris)	Dispersive analysis of isospin breaking in Kl4 decays
10:45		*Coffee*

Late Morning Session

Chair: H.-W. Hammer		**Chiral Perturbation Theory II**
11:05	Jose Pelaez (Madrid)	Quark mass and N_c dependence of meson-meson scattering: Phases and resonances from standard and unitarized CHPT
11:40	Peter Bruns (Regensburg)	Coupled channel Bethe-Salpeter approach to pion-nucleon scattering
12:15		*End of Session*
12:30		*Lunch*

Early Afternoon Session

Chair: Nora Brambilla		**Heavy Quark Physics I**
14:00	Bernd Kniehl (Hamburg)	Reconciling J/Psi production at HERA, RHIC, Tevatron and

		LHC with NRQCD factorization at next-to-leading order
14:35	Andre Hoang (Vienna)	Top quark mass at LHC
15:10	Alex Rothkopf (Tokyo)	Proper heavy quark potential from lattice QCD
15:45	Antonio Vairo (Munich)	The correlator of Polyakov loops at NNLO
16:20		*Coffee*

Late Afternoon Session

Chair: Nora Brambilla		**Heavy Quark Physics II**
17:00	York Schroeder (Bielefeld)	Quark mass effects in QCD thermodynamics
17:35	Christoph Hanhart (Jülich)	How to identify hadronic molecules
18:10	Peter Petreczky (BNL)	Effective field theory approach for quarkonium at finite temperature
18:45		*End of Session*
19:00		*Dinner: Invitation by the Wilhelm und Else Heraeus-Stiftung*

Monday, February 14th, 2011

Early Morning Session

Chair: H.-W. Hammer		**Cold Atoms III**
09:00	Yvan Castin (Paris)	Four-body Efimov effect
09:35	Arnoldas Deltuva (Lisbon)	Universality in four-body scattering
10:10	Dmitri Fedorov (Aarhus)	Three boson systems near a Feshbach resonance in a two-channel zero-range model
10:45		*Coffee*

Late Morning Session

Chair: H.-W. Hammer		**Cold Atoms IV**
11:05	Kerstin Helfrich (Bonn)	Three bosons in two dimensions
11:40	Dima Petrov (Paris)	Parametric excitation of a 1D gas in integrable and non-integrable cases
12:15		*End of Session*
12:30		*Lunch*

Early Afternoon Session

Chair: Ulf-G. Meißner		**Chiral Perturbation Theory III**
14:00	Akaki Rusetsky (Bonn)	Effective field theories in a finite volume
14:35	Feng-Kun Guo (Bonn)	Extraction of light quark mass ratio from heavy quarkonia transitions
15:10	Bastian Kubis (Bonn)	Rescattering effects in η and η' decays
15:45	Norbert Kaiser (Munich)	Low-energy pion-photon reactions and chiral symmetry
16:20		*Coffee*

Late Afternoon Session

Chair: Evgeny Epelbaum		**Few-Baryon Systems I**
17:00	Ruprecht Machleidt (Moscow, Idaho)	The nuclear force problem: have we finally reached the end of the tunnel?

17:35	Hermann Krebs (Bochum)	Three-nucleon forces with explicit Δ fields
18:10	Nasser Kalantar-Nayestanaki (KVI)	What have we learned about three-nucleon forces at intermediate energies
18:45		*End of Session*
19:00		*Dinner*

Tuesday, February 15th, 2011

Early Morning Session

Chair: Evgeny Epelbaum		**Few-Baryon Systems II**
09:35	Silas Beane (New Hampshire/Bern)	Hadron interactions from lattice QCD
10:10	Dean Lee (North Carolina)	Nuclear physics from lattice effective field theory
10:45		*Coffee*

Late Morning Session

Chair: Ulf-G. Meißner		**Hadronic contributions**
11:05	Hartmut Wittig (Mainz)	The hadronic vacuum polarization contributions to $(g-2)_\mu$ from lattice QCD
11:40	Antonio Pineda (Barcelona)	The muonic hydrogen Lamb shift and the proton radius
12:15		*End of Session*
12:30		*Lunch*

Early Afternoon Session

Chair: Nora Brambilla		**Heavy Quark Physics III**
14:00	Binsong Zou (IHEP)	Prediction of super-heavy $N^\star$ and $\Lambda^\star$ with hidden charm and beauty
14:35	Qiang Zhao (IHEP)	A coherent view of the charmonium hadronic and radiative decays
15:10	Mei Huang (IHEP)	Interplay between chiral and deconfinement phase transitions
15:45		*Coffee*

Late Afternoon Session

Chair: Nora Brambilla		**Heavy Quark Physics IV**
17:00	Jacopo Ghiglieri (Munich)	Effective field theories for heavy quark(onia) at finite temperature
17:35	Paul Romatschke (Frankfurt)	Hadrodynamics: a tool for strongly coupled systems
18:10	Yu Jia (IHEP)	Some novel development in quarkonium electromagnetic transitions
18:45		*End of Session*
19:00		*Dinner*

Wednesday, February 16th, 2011

Early Morning Session	
Chair: Evgeny Epelbaum	**Few-Baryon Systems III**
09:00 Daniel Phillips (Athens, Ohio)	Electromagnetic properties of single-neutron halo nuclei from effective field theory
09:35 Rocco Schiavilla (JLab)	Electromagnetic processes on few-nucleon systems at low energies
10:10 Doron Gazit (Jerusalem)	Inferring nuclear structure from electroweak reactions
10:45	*Coffee*
Late Morning Session	
Chair: Evgeny Epelbaum	**Few-Baryon Systems IV**
11:05 Vadim Baru (Jülich))	A high-accuracy calculation of the pion-deuteron scattering length
11:40 Johan Haidenbauer (Jülich)	Hyperon-nucleon and hyperon-hyperon interactions in chiral effective field theory
12:15	*End of Session*
12:30	*Lunch*
Early Afternoon Session	
Chair: Nora Brambilla	**Heavy-Quark Physics V**
14:00 Jianwei Qiu (BNL)	QCD factorization and heavy quarkonium production
14:35 Pietro Falgari (Utrecht)	Threshold resummation of heavy coloured particle cross section
15:10 Evgeny Epelbaum (Bochum)	Concluding remarks
15:20	*End of Workshop*

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Monte Carlo Calculations for Fermi Gases

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Ultracold atomic gases have become a fertile environment for cultivating and examining diverse varieties of physical phenomena. Many theories of condensed matter can be realized through inventive trapping techniques. Furthermore, the purity of the gases permits accurate, systematically improvable calculations, often employing field theoretic methods.

Our work has focused on Monte Carlo calculations for Fermi gases [1], especially in the unitary scattering limit. Here, there are dimensionless numbers and functions which are universal, depending only on one characteristic length scale, say the mean interparticle spacing. One role of numerical calculations is to determine these universal properties from first principles.

A number of Monte Carlo methods have been applied to this problem [2]. In our recent and ongoing work studying the properties of the unitary Fermi gas near the superfluid/normal critical temperature, we employ a generalization of diagrammatic determinant Monte Carlo [3]. We found a reduction in autocorrelation time with a new type of configuration update. We also explored the slightly spin-imbalanced unitary Fermi gas using a sign-quenched method of updating, where the effects of the sign are taken into account in observables. For the critical temperature we find [4]

$$T_c(\Delta\mu)/\varepsilon_F \;=\; 0.171(5) \;+\; T_2\,(\Delta\mu/\varepsilon_F)^2\,.$$

For our data T_2 is consistent with 0, and from the fit uncertainty we estimate a lower bound $T_2 > -0.5$ (at 68% CL). We find for the chemical potential $\mu/\varepsilon_F = 0.429(7)$, independent of $\Delta\mu$ within uncertainties for $\Delta\mu/\varepsilon_F < 0.2$.

Another quantity we can compute is Tan's contact. This enters as the sole long-distance quantity in OPE relations [5]. For the spin-balanced gas at $T = T_c$, our preliminary result for the contact is [6]

$$C(T_c) \;=\; 0.1102(11)\,\varepsilon_F^2 V \;=\; 3.26(3)\,k_F N\,.$$

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From Few to Many

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Strongly interacting many-body systems pose a constant challenge to theory. For example, most results for non-relativistic spin-1/2 particles interacting through a large scattering length have been obtained numerically [1]. However, Shina Tan recently derived analytically and with novel methods remarkable universal relations that hold for any state of this system [2]. They are particularly important since the central quantity (the so-called contact) controls amongst other things the thermodynamics of the many-body ensemble. Several other methods have been used to rederive these relations (see e.g. Ref. [3] for a summary) but one particular powerful one was discussed in this talk. In Ref. [4] it was shown that these relations can be rederived using the so-called operator product expansion which is a short-distance expansion that has been employed to various strongly-interacting systems (e.g. ising model). This method has also allowed to derive new universal relations for the fermionic many-body system that were previously unknown. We have recently applied this approach also to bosonic systems with a large scattering length [5] and have derived a number of new universal relations. This system is special because it will display the Efimov effect. This is encoded in the quantum field theoretical description through a three-body force with an anomalous scaling dimension [6]. It's experimental signature is discrete scale invariance and it is of importance in atomic, nuclear and particle physics [7]. The versatility of the operator product expansion guarantees that further universal relations for additional systems (e.g. fermionic systems with three spin states) can be derived. The importance of the three-body force and therefore of the Efimov effect shows up as a second "contact" in the bosonic universal relations.

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Universal features of weakly and strongly interacting few-body systems

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Universality arises in many different branches of physics. Generally speaking, a given phenomenon is referred to as universal when the observables for different physical systems can be collapsed to a single point or curve. The talk given at the "Strong interactions: From methods to structures" workshop summarized our theoretical investigations of universal aspects of ultracold bosonic and fermionic gaseous few-atom systems, which share certain features with few-nucleon systems and can thus be regarded as model systems. In the ultracold regime, where the deBroglie wave length is large compared to the range of the atom-atom interaction potentials, the collisions between atoms become so slow that the details of the interactions are, to leading order, neglegible. In this regime, the dynamics of few-atom systems is governed by a few "effective parameters" (such as the s-wave scattering length) and independent of the details of the underlying two-body potentials. As a consequence, the true atom-atom potential can be replaced by a model potential that is most suitable for the numerical or analytical techniques employed. For example, we employ a "soft" Gaussian potential in our stochastic variational studies [1,2,3] and a zero-range pseudo-potential in our analytical analysis. As a first example, we analyzed the behavior of weakly-interacting Bose gases in terms of effective, and presumably universal, N-body interactions. This study is partially motivated by Ref. [4]. As a second example, we investigated the behavior of strongly-interacting two-component Fermi gases with equal and unequal masses [5,6]. Implications of our studies for on-going experimental efforts were discussed. Support by the NSF through grant PHY-0855332 and the ARO is gratefully acknowledged.

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Functional RG for few-body systems

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The functional renormalisation group for the one-particle-irreducible effective action has proved to be a powerful tool for analysing a variety of physical systems [1]. In particular, it has been applied to fermionic matter close to the unitary limit [2,3]. As a field-theoretic approach, it can be easily matched on to the effective field theories that are now being used to describe both nuclear and atomic systems at low energies.

The input into these many-body calculations is fixed by applying the same RG to few-body systems. The first studies used only two-body physics, within a local trucation of the action [2,3,4]. This was then extended to include three-body interactions, again with a local form [5,6]. In three-body systems where the particle exchange force is attractive, an Efimov limit cycle is obtained, with a very good approximation to the discrete scaling factor [5,7]. The full set of local terms needed to describe the four-body system (dimer-dimer scattering) includes terms where one of the dimers can break up into its constituent atoms, as noted by Schmidt and Moroz for the case of bosons [7].

Four-fermion systems with a full local truncation of the action were studied in Ref. [8]. The dimer-dimer scattering length obtained with the RG agrees very well with the value from standard few-body calculations. Moreover the result is only weakly dependent on the choice of the regulator function used in the RG evolution. Anomalous dimensions for three- and four-body forces have also been determined using this method and, in the fermionic case, these show that such forces are all highly irrelevant.

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Functional renormalization and ultracold quantum gases

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Functional renormalization is a modern method mainly used to study strongly interacting field theories. An exact flow equation for the one-particle irreducible effective action [1] is solved approximately by truncating the most general form of the action.

This method was employed to study different aspects of ultracold quantum gases. For example, a detailed picture of the BCS-BEC crossover for fermions with two components has been obtained [2]. Observables such as the gap, the radius of the Fermi sphere or the dispersion relation have been calculated for all values of the crossover parameter ak_F including the unitarity point where it diverges. The critical temperature interpolates between a weakly interacting Fermi gas described by BCS theory including Gorkov's correction and a gas of bosonic bound states with repulsive interaction.

For interacting bosons with local repulsive interaction many thermodynamic properties have been calculated in the superfluid phase. This includes the temperature and density dependence of pressure, energy and entropy-density, superfluid and condensate-fraction, correlation length, specific heat, isothermal and adiabatic compressibility and various sound velocities [3].

Functional renormalization was also used successfully to study interesting few-body physics (see the contribution of M. Birse to this conference). One example is the Efimov effect for three species of fermions with identical mass and scattering length. In the functional renormalization group description this shows up as a limit cycle [4,5]. Based on a continuity argument one can predict quantum phase transitions from a BCS type phase to one dominated by three-body bound states and further to a BEC type phase [4]. After extending the approach to non-equal scattering length it can be used to explain recently measures three-body loss rates in lithium [6].

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Chiral Perturbation Theory in New Surroundings

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This talk describes some of the recent work done in Lund in Chiral Perturbation Theory (ChPT) and Effective Field Theory (EFT).

It recently became clear that ChPT can also be applied to situations where momenta are not soft. The arguments are based on the fact that chiral logarithms come from soft parts of the loop integrals and that these are well predicted as soon as a sufficiently complete Lagrangian is used for the neighbourhood of the relevant process and kinematics [1,2]. I will discuss the application to $K \to \pi\pi$ [1] and to a large set of formfactors: the pion and kaon electromagnetic formfactor, the pion scalar formfactor, $B, D \to \pi, H, \eta$ and $B \to D$ vector transitions [3,4]. The arguments are checked using extra terms and/or different formalisms. A two-loop check can be done for the pion electromagnetic and scalar formfactor.

A second area in which we made progress is the calculation of leading logarithms to a much higher loop level than before in a massive EFT. I will describe the principle behind the calculations and results for the $O(N)$ sigma model [5,6]. We also get the leading large N results to all orders. Quantities discussed are the mass, decay constant, vacuum expectation value, scalar and vector formfactors, and meson-meson scattering.

The last part concerns the ongoing work on two-loop calculations for symmetry breaking patterns other than standard ChPT. Here we discuss the symmetry breaking patterns for the case of N_F fermions in a complex, real or pseudoreal gauge group representation. Calculated so far are the mass, decay constant and vacuum expectation value [7] and meson-meson scattering [8]. We founds some large N_F relations for scattering amplitudes between the three cases. This work is relevant for models of dynamical symmetry breaking in the standard model.

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Nucleon magnetic moments and electric polarizabilities with lattice QCD in background electric fields

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The response of hadrons to low-energy electromagnetic probes is well described by the first few terms in a multi-pole expansion, which provide information about the hadrons internal structure. Near the chiral limit, nucleon polarizabilities arise from the deformation of the charged pion cloud, and are highly constrained by effective interactions that emerge in the low-energy limit of QCD. Lattice QCD will play a crucial role in validating this low-energy picture, and the electromagnetic polarizabilities provide an area in which the lattice will influence phenomenology.

We describe a new method of computing charged and neutral hadron electromagnetic properties using lattice QCD and background fields. Previously, we have shown how to determine the electric polarizabilities of charged and neutral pseudo scalar mesons with lattice QCD [1,2]. We have recently extended this work to nucleons [3].[1] Treating the spin relativistically is necessary to account for all effects at second order in the strength of the applied electric field. To determine the electric polarizability, we show that a background field analogue of the Born subtraction is necessary. We demonstrate such a method, focussing on the determination of the nucleon magnetic moments. Both the precision and values are consistent with independent methods utilizing momentum extrapolations of three-point functions [5].

We conclude with a summary of current and future results as well as refinements which must be made to compare with experiment.

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[1]With suitable choices of space and/or time varying background electromagnetic fields, one can compute the nucleon spin polarizabilites as well [4].

Dispersive analysis of isospin breaking in $K_{\ell 4}$ decays

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The NA48/2 experiment has provided very accurate low-energy data on the difference of S- and P-wave $\pi\pi$ phase shifts through a careful analysis of $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ decays [1]. It was pointed out that this high level of accuracy required one to take into account isospin-breaking effects [2]. The contributions from real and virtual photons can be treated (and have been removed) experimentally, estimating the Coulomb exchanges and incorporating radiative processes by a Monte-Carlo treatment. On the other hand, the effects from the mass differences between charged and neutral pions must be determined from a theoretical analysis. The induced isospin-breaking corrections can be computed in the framework of chiral perturbation theory, assuming particular values of the $\pi\pi$ scattering lengths a_0^0, a_0^2. But one can bypass these assumptions using an alternative and more general dispersive approach to reconstruct the amplitudes of interest [3].

The isospin-breaking corrections to Watson's theorem, responsible for the difference between the phases of the $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ form factors and those from $\pi\pi$ scattering in the isospin limit, fall into three categories: final-state phase-space difference, $\pi^0\pi^0 \to \pi^+\pi^-$ rescattering, isospin-breaking in $K_{\ell 4}$ form factors between $\pi^+\pi^-$ and $\pi^0\pi^0$ final states. These isospin-breaking contributions induce also a dependence of the phase shifts on the leptonic invariant mass s_l. Both $\pi\pi$ scattering amplitudes and $K_{\ell 4}$ form factors are reconstructed dispersively in order to compute the difference between the measured phases in $K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$ and the corresponding phases in the isospin limit, at next-to-leading order, and at first order in isospin breaking. We then assess these effects exploiting available estimates of the relevant low-energy counterterms. We agree with existing works based on chiral perturbation theory [2] when we take the $\pi\pi$ scattering lengths predicted in chiral perturbation theory. But when we vary a_0^0, a_0^2 in the universal band allowed by Roy equations, isospin-breaking corrections to the phase shifts can change noticeably. These results will be used to reanalyse $K_{\ell 4}$ phase shifts to determine the pattern of $N_f = 2$ chiral symmetry breaking [4].

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Quark mass dependence of meson-meson scattering: phases and resonances from standard and unitarized Chiral Perturbation Theory

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We use one and two-loop Chiral Perturbation Theory (ChPT) to study the quark mass dependence of meson meson elastic scattering phase shifts and resonance poles. Phases are studied [1] within SU(2) standard ChPT and we show the soft mass dependence once phases are expressed in terms of momentum. We also show how the range of applicability can be extended by means of unitarization. Resonances are generated through unitarized ChPT from a dispersion relation in the form of the Inverse Amplitude Method, either within SU(2) to one loop [2] and to two loops [3], or within the SU(3) formalism [4] to one loop. Details can also be found in the review [5]. Here we show a good agreement with existing lattice results on isospin 2 phases, the ρ mass, f_π and the highest isospin scattering lengths. In addition we provide predictions for ρ couplings and all the parameters for the $f_0(600)$, $\kappa(800)$ and $K^*(892)$. The results may be used as a guideline for lattice studies and as insight on the structure of the lightest hadronic resonances, particularly the controversial light scalars.

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Coupled-channel approach to pion-nucleon-scattering

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The analysis of meson-baryon scattering in the resonance region is a difficult non-perturbative problem for which, up to this date and to the best of our knowledge, only model treatments exist. It is the aim of the work presented in this talk (see also [1]) to see how far one can get in the description of meson-baryon scattering if one keeps a one-to-one correspondence of the terms in the scattering amplitude to dimensionally regularized Feynman graphs. This correspondence allows for a natural and straightforward method to implement gauge invariance in a chiral unitary framework for meson photoproduction, where the meson-baryon scattering amplitude discussed here serves as an "extended vertex" guaranteeing exact (two-particle) unitarity in the subspace of meson-baryon states.

To keep the abovementioned correspondence to Feynman graphs, we chose to apply the Bethe-Salpeter equation to iterate our potential, derived from the contact terms of the leading and next-to-leading order chiral meson-baryon Lagrangian, to infinite order. It is a clear drawback of the method under discussion that Born-terms can not be iterated, as the corresponding Feynman graphs would yield multiloop integrations which could only be treated numerically, introducing some cutoff regulator functions destroying the exact correspondence to Feynman graphs aimed at here.

As an example for the outcome of our model, we compare our results for the pion-nucleon s-wave scattering amplitudes to the data analysis provided by the SAID program. Though we fit only data up to 1.56 GeV, our description of the S11 partial wave above this energy works rather well. In particular, besides generating the $S_{11}(1535)$ resonance, we also obtain one more resonance pole structure which can be associated with the $S_{11}(1650)$. On the other hand, the $S_{31}(1620)$ is not generated in our approach.

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Reconciling J/ψ production at HERA, RHIC, Tevatron and LHC with NRQCD factorization at next-to-leading order

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We calculate the cross section of inclusive direct J/ψ photoproduction [1] and hadroproduction [2] at next-to-leading order (NLO) within the factorization formalism of nonrelativistic quantum chromodynamics (NRQCD) [3], including the full relativistic corrections due to the intermediate ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$ color-octet (CO) states. We perform a combined fit of the CO long-distance matrix elements to the transverse-momentum (p_T) distributions measured by CDF [4] at the Fermilab Tevatron and H1 [5,6] at DESY HERA and demonstrate that they also successfully describe the p_T distributions from PHENIX [7] at BNL RHIC and CMS [8] at the CERN LHC as well as the photon-proton c.m. energy and (with worse agreement) the inelasticity distributions from H1 [5,6]. This provides a first rigorous test of NRQCD factorization at NLO. In all experiments, the CO processes are shown to be indispensable.

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What Top Mass is measured at the LHC ?

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At LHC and the Tevatron the top mass is determined from comparing measured distributions, such as the top invariant mass distribution, with corresponding predictions from Monte-Carlo (MC) generators. Thus the quoted top mass is the MC mass parameter. In principle, the MC top quark mass parameter corresponds to a specific mass scheme (MC-scheme) that depends on the way how the perturbative part of the event generator, i.e. the parton shower, is implemented and to which extend higher order matrix element corrections are included.

Two arguments show that the top quark MC scheme is not the pole scheme. First, the parton shower relies on a leading-log approximation for soft and collinear radiation and, second, the shower evolution is restricted from below by the shower cutoff of 1 GeV, which acts as an IR cutoff for the perturbative contributions. Virtual contributions needed to specify the pole scheme are absent and the IR cutoff protects the MC top mass scheme from low-momentum renormalon contributions that plague the pole mass scheme. Up to now, real and virtual corrections needed to specify the MC scheme at $\mathcal{O}(\alpha_s)$ have not yet been quantified. This restricts the application of the top mass in the MC scheme in precision physics.

Using Soft-Collinear-Effective-Theory it has recently become possible to make first principle factorization predictions for jets initiated by heavy quarks and define a jet mass scheme which the above issues. For e^+e^- collisions the hemisphere jet mass and thrust distributions can be computed [1]. These results allow the top mass to be determined from the experimental distributions with precise control of the scheme and of the theoretical uncertainties. On the other hand, they could also be used to relate the MC top quark mass scheme to the jet mass scheme [2,3]. To implement such a program for hadron collider MCs, corresponding factorization calculations with the jet mass still have to be carried out.

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Proper Heavy Quark Potential from Lattice QCD

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We refine our proposal [1] on a non-perturbative derivation of the spin-independent complex potential for the two-body system consisting of a heavy quark and anti-quark at any temperature. This non-relativistic description is based on the separation of scales

$$\frac{\Lambda_{\rm QCD}}{m_Q c^2} \ll 1, \ \frac{T}{m_Q c^2} \ll 1, \frac{\mathbf{p}}{m_Q c} \ll 1, \tag{1}$$

and utilizes the concept of quantum mechanical path integrals [2] for each heavy constituent. It yields the following expression for the static potential in terms of the spectral function of the thermal Wilson loop

$$V^{(0)}(R,t) = -i\frac{\partial_t W_\square(R,t)}{W_\square(R,t)} = \frac{\int d\omega\, \omega\, e^{i\omega t}\rho_\square(\omega,R)}{\int d\omega\, e^{i\omega t}\rho_\square(\omega,R)}. \tag{2}$$

If the spectral peak structure is well defined (e.g. Breit-Wigner or Gaussian type) a potential with real part (peak position) and imaginary part (peak width) is obtained.

The analytical continuation of the real-time thermal Wilson loop to Euclidean times

$$W_\square(R,-it) = W_\square(R,\tau) = \int d\omega e^{-\omega\tau}\rho_\square(\omega,R) \tag{3}$$

allows us to infer the spectral functions required for the determination of the potential from lattice QCD simulations, using the Maximum Entropy Method[3]. A numerical evaluation in the quenched approximation ($T = 0.78, 1.17, 2.33 T_C$) suggests that the growth of the imaginary part, rather than the Debye screening of the real-part, will lead to a melting of bound states at temperatures above the deconfinement transition.

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The Polyakov Loop and Correlator of Polyakov Loops at NNLO

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In [1], we have studied the Polyakov loop and the correlator of two Polyakov loops at finite temperature in the weak-coupling regime. We have calculated the Polyakov loop in a colour representation R, $\langle L_R \rangle$, up to order g^4:

$$\langle L_R \rangle = 1 + \frac{C_R \alpha_s}{2} \frac{m_D}{T} + \frac{C_R \alpha_s^2}{2} \left[C_A \left(\ln \frac{m_D^2}{T^2} + \frac{1}{2} \right) - n_f \ln 2 \right] + \mathcal{O}(g^5).$$

Our result disagrees with the old determination of [2], for understood reasons, but agrees with the recent one of [3]. The calculation of the correlator of two Polyakov loops, $C_{\rm PL}(r, T)$, is performed at distances r shorter than the inverse of the temperature T and for electric screening masses m_D larger than the Coulomb potential. In this regime, the calculation is new and accurate up to order $g^6 (rT)^0$:

$$\begin{aligned} C_{\rm PL}(r, T) = \frac{N^2 - 1}{8N^2} \Bigg\{ & \frac{\alpha_s(1/r)^2}{(rT)^2} - 2 \frac{\alpha_s^2}{rT} \frac{m_D}{T} + \frac{\alpha_s^3}{(rT)^3} \frac{N^2 - 2}{6N} \\ & + \frac{1}{2\pi} \frac{\alpha_s^3}{(rT)^2} \left(\frac{31}{9} C_A - \frac{10}{9} n_f + 2\gamma_E \beta_0 \right) + \frac{\alpha_s^3}{rT} \Bigg[C_A \left(-2 \ln \frac{m_D^2}{T^2} + 2 - \frac{\pi^2}{4} \right) \\ & + 2 n_f \ln 2 \Bigg] + \alpha_s^2 \frac{m_D^2}{T^2} - \frac{2}{9} \pi \alpha_s^3 C_A \Bigg\} + \mathcal{O}\left(g^6 (rT), \frac{g^7}{(rT)^2} \right). \end{aligned}$$

In order to interpret the result, we have also evaluated the Polyakov-loop correlator in an effective field theory framework that takes advantage of the hierarchy of scales in the problem and makes explicit the non-relativistic bound-state dynamics [4]. In the effective field theory framework, we show that the Polyakov-loop correlator is at leading order in the multipole expansion the sum of a colour-singlet and a colour-octet quark-antiquark correlator, which are gauge invariant, and compute the corresponding colour-singlet and colour-octet free energies.

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How to identify hadronic molecules

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Many years ago Weinberg proposed a criterion that allows one to quantify from data the molecular component of a bound state located in mass close to a continuum channel [1]. This criterion can, under certain conditions, be generalized to resonances [2]. The central finding of this picture is that the effective coupling constant of a state to the continuum channel becomes maximal, if the state is predominantly a molecule made of the corresponding particles. In the talk I discuss the implications of this picture. E.g., within this scheme it is possible to properly predict $f_0 \to \gamma\gamma$ [3] under the assumption that the $f_0(980)$ is a $\bar{K}K$ molecule. For another state, the $D_s(2317)$ (as well as its spin partner $D_s^*(2460)$) one can predict the hadronic width reliably, once it is assumed to be a KD molecule [4]. The same scheme also allows one to predict the quark mass dependence of molecular states that could be checked using lattice QCD. Again for $D_s(2317)$ and $D_s^*(2460)$ we find a quite strong light quark mass or equivalently pion mass dependence of the mass of the states [5,6] – since of a $c\bar{s}$ state the light quark mass dependence enters typically via loops and their contribution gets maximal when the effective coupling gets maximal – and an unusual, linear kaon mass dependence of the masses. The latter is a natural consequence of the molecular nature: the mass of the molecule follows the threshold since the quark mass dependence of the binding energy is weak [6].

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Effective field theory approach to quarkonium at finite temperature

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Quarkonium can be used to probe the properties of hot strongly interacting matter produced in heavy ion collisions [1]. Nevertheless first principle calculations of quarkonium properties are still missing. Direct lattice calculations of the quarkonium spectral functions turned out to be very difficult [2]. Attempts to study quarkonium properties using potential models have been made, but unlike in the zero temperature case the form of the potential is not known. The effective field theory approach to quarkonium at finite temperature can address these problems [3]. As in the case of zero temperature the quark anti-quark potential appears as a parameter of the effective field theory Lagrangian. The form of the potential and whether it is effected by the medium depends on the relation of the thermal scales T and m_D (the Debye mass) and the zero temperature scales, the bound state size r and the binding energy E_{bin}. If $E_{bin} \gg T$ there are no thermal correction to the potential. On the other hand if $E_{bin} \ll T$ there are thermal corrections to the potential and their nature is different for $r \ll 1/T$ (short distance regime) and for $r \gg 1/T$ (large distance regime). In the former case one first has to integrate out the scale $1/r$ and then the scale $1/T$. Temperature effects show up as power law corrections in the potential proportional to powers T and m_D. In the later case one first integrates out the temperature scale, which is equivalent to the hard thermal loop resummation and then the scale $1/r$. In the large distance regime the potential is exponentially screened for $r \sim 1/m_D$ [3]. At these distances the singlet $Q\bar{Q}$ potential equals to the singlet free energy calculated in [4]. Bottomonium properties at finite temperature have been calculated in the effective field theory approach assuming that calculations can be done in the short distance regime [5]. For charmonium such an assumption is not justified and the corresponding spectral functions can be calculated using effective field theory inspired potential model [6].

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Four-body Efimov effect

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The few-body problem with resonant two-body s-wave interaction (infinite scattering length) can now be studied experimentally with cold atoms. In particular, the three-body Efimov phenomenon, consisting in the existence of an infinite number of trimer states with an asymptotically geometric spectrum in the vicinity of a zero energy accumulation point [1], has now experimental evidence with same spin bosons and with fermions in three different spin states [2].

On the contrary, the four-body Efimov effect has remained elusive. For same spin state bosons, as pointed out in [3], it is *a priori* washed out by the three-body Efimov effect: Whereas low lying tetramers are possible [4], a tetramer state with an energy arbitrarily close to zero has eventually an energy larger than an Efimov trimer state and decays into this trimer plus a free atom [5].

We have found a system where a four-body Efimov effect takes place [6]: It is made of three same spin state fermions of mass M interacting only with a lighter particle of mass m. The mass ratio $\alpha = M/m$ can be used as a control knob: It was known that this system experiences a three-body Efimov effect if and only if $\alpha > \alpha_c(2;1) \simeq 13.607$ [1,7]. Using a combination of analytical arguments [8] and numerical solution of an integral equation, we show that an infinite number of Efimov tetramers exist over the interval of mass ratio $\alpha_c(3;1) < \alpha < \alpha_c(2;1)$, with $\alpha_c(3;1) \simeq 13.384$. The four-body Efimov exponent $|s|$ is also calculated as a function of α over that interval, and the experimental feasibility. is discussed.

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Universality in four-body scattering

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We study the four-particle system by solving exact Alt, Grassberger, and Sandhas (AGS) equations for the transition operators [1] in the momentum-space framework [2]. The method has been applied successfully to the description of four-nucleon reactions [2,3] and was extended to the four-boson system with large two-boson scattering length a [4]. In the latter case the three-boson Efimov effect [5] has an impact on the the four-boson observables. The unitary limit ($a \to \infty$) results for the atom-trimer scattering length, effective range, phase shifts, elastic and inelastic cross sections in reactions with highly excited trimers (at least 2nd excited state) were found to be related to the trimer binding energy in a universal way [4]. Furthermore, the existence of two tetramers for each Efimov trimer was predicted [6,7]. However, only the two tetramers associated with the trimer ground state are true bound states that have been studied in all the details using standard bound state techniques [6,7]. Higher tetramers are unstable bound states that lie above the lowest atom-trimer threshold and for this reason their universal properties were far less known; we determined their positions and widths using proper scattering calculations [8]. In contrast to [7], we found that the shallow tetramer intersects the atom-trimer threshold twice and in a particular regime becomes an inelastic virtual state. As a consequence, the atom-trimer scattering length exhibits a resonant behaviour that might be observed as a resonant enhancement of the trimer relaxation in the ultracold mixture of atoms and excited trimers.

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Three bosons in two dimensions

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In this talk I discussed two-dimensional bosonic gases exhibiting a large two-body scattering length. Within an effective field theory for resonant interactions, we calculate bound-state and scattering observables up to next-to-leading order, i.e. with the inclusion of the two-body effective range. We are especially interested in three-body observables such as the three-body binding energies, the atom-dimer scattering properties, and the three-body recombination rate. Significant effective range effects in the vicinity of the unitary limit are found and their implications are briefly discussed. More details can be found in Ref. [1].

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Parametric Excitation of a 1D Gas in Integrable and Nonintegrable Cases

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Ultracold gases are ideal candidates for studies of fundamental differences between integrable and nonintegrable many-body dynamics. The main question is what measurement should one perform on a system in order to conclude on its integrability. The field of quantum chaos suggests to look at its spectral statistics [1]. If energy levels are not correlated, we are dealing with an integrable or regular system. If, in contrast, levels repel each other, the system is not integrable. Another signature of integrability is the localization of eigenstates of a regular system in a certain physically meaningful basis, which suggests the dynamical probe of integrability: an excited initial state localized in this basis will stay localized during the temporal evolution.

In this work [2] we compare responses of highly excited integrable and non-integrable systems to an external time-dependent perturbation. We explore the idea that a perturbation localized in the same space as the eigenstates of the integrable system probes its local density of states, whereas in the nonintegrable case the states are delocalized, and the perturbation, no matter localized or not, couples all of them. Considering two 1D models on a ring we demonstrate that integrable systems can be much more stable with respect to slow variation of their Hamiltonian than nonintegrable ones. Namely, we consider the model of a single mobile impurity in a Fermi gas and the Lieb-Liniger model, and study their response to a periodic modulation of the coupling constant. This perturbation is localized in the many-body momentum space as it only changes the relative momentum of an atom pair. We show that the non-integrable system is sensitive to excitations with frequencies as low as the many-body mean level spacing, which is exponentially small, whereas the threshold frequency in the integrable case is much larger and scales polynomially with the system size.

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Effective Field Theories in a Finite Volume

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We review various applications of effective field theory methods in a finite volume for the extraction of the characteristics of unstable particles from lattice QCD calculations. The talk is based on the material published in the papers [1,2], as well as on the results of ongoing investigations [3].

As the first example, the scalar mesons $f_0(980), a_0(980)$ are considered. We formulate criteria that distinguish, on one side, between hadronic molecules and tightly bound quark states, and, on the other side, between ordinary $q\bar{q}$ and tetraquark $qq\bar{q}\bar{q}$ states. Using these criteria will enable one to study the nature of scalar mesons on the lattice [1].

As the second example, we formulate a procedure to calculate resonance matrix elements (the magnetic moments of resonances, the electromagnetic form factors, etc) on the lattice by using the background field method. In particular, we discuss the problems which arise when the infinite-volume limit of these matrix elements is performed. These problems have been analyzed in detail for the 1+1-dimensional field theory by using a non-relativistic effective Lagrangian technique [2]. Additional complications arise in the 3+1-dimensional case. In this talk, ways to circumvent these complications have been discussed, see also Ref. [3].

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Extraction of light quark mass ratio from heavy quarkonia transitions

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The $\psi' \to J/\psi\pi^0(\eta)$ was widely used in extracting the light quark mass ratio m_u/m_d [1,2,3]. However, the extracted value using the PDG value for the measured branching fractions is 0.39 ± 0.02. It is not compatible with the value obtained using the pseudoscalar meson masses in chiral perturbation theory. We show that the so-extracted quark mass ratio suffers from very large corrections from the intermediate charmed meson loops [4]. In fact, various phenomenological calculations already suggested that heavy meson loops could play an important role in the decays of heavy quarkonia (for an overview, see [5]). Since $M_{c\bar{c}} - 2M_D \sim \Lambda_{\rm QCD} \ll M_D$, the intermediate charmed mesons can be dealt with non-relativistically in a non-relativistic effective field theory framework [4,6]. It was shown that the heavy meson-loop effects were also enhanced in the transitions with the emission of one pion between two P-wave heavy quarkonia. On the contrary, for the transitions between one S-wave and one P-wave heavy quarkonia, the loops need to be analyzed case by case and often appear to be suppressed [7]. For a detailed power counting analysis, see Ref. [6]. In Ref. [8], we propose that the light quark mass ratio can be extracted from the transitions $\Upsilon(4S) \to h_b\pi^0(\eta)$, where the bottom meson loops are expected to be suppressed, to be measured in the future.

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Rescattering effects in η and η' decays

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Final-state interactions in meson decays into three particles with small excess energy can be analyzed perturbatively in a variant of non-relativistic effective field theory [1,2], originally developed to study cusp effects (see Ref. [3] for a review of various applications). Such rescattering effects are of high importance in $\eta \to 3\pi$, which plays a central role in precision determinations of the light quark mass ratios. We have analyzed the Dalitz plot parameters for this decay [4] and in particular can reconcile the precise experimental values for the $\eta \to 3\pi^0$ slope parameter α with seemingly unsuccessful chiral predictions [5]: we find $\alpha = -0.025 \pm 0.005$, to be compared with the current Particle Data Group average $\alpha = -0.0317 \pm 0.0016$.

A precise understanding of rescattering and the resulting *imaginary parts* of the decay amplitudes furthermore allows to compare α to the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot parameters in a consistent fashion [4]: the latter's most recent experimental determination [6] seems to be inconsistent with the neutral decay channel. Higher-order isospin violation [7] plays only a minor role.

To obtain reliable descriptions of final-state interactions also at somewhat higher energies and resum rescattering effects beyond perturbation theory, one has to resort to dispersion theoretical treatments à la Khuri and Treiman. Applied to hadronic η' decays, these may, in addition to cusp effects [8], offer an alternative access to quark masses, or allow to study $\pi\eta$ scattering.

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Low-Energy Pion-Photon Reactions and Chiral Symmetry

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In this talk, I review the description of low-energy pion-Compton scattering in chiral perturbation theory. At one-loop order, the effects due to the pion structure consist of the electric and magnetic polarizabilities (subject to the constraint $\alpha_\pi + \beta_\pi = 0$) and a unique pion-loop correction interpretable as photon scattering off the "pion-cloud around the pion". The latter compensates in the differential cross section $d\sigma/d\Omega_{\rm cm}$ partly the reduction effects due to the polarizabilities [1]. The two-loop corrections to charged pion-Compton scattering, first calculated by Bürgi [2] and recently completed and reevaluated by Gasser et al. [3] are relatively small in the low-energy region $\sqrt{s} < 4m_\pi$. Therefore chiral perturbation theory leads to firm predictions for the pion polarizabilities [3]: $\alpha_\pi - \beta_\pi = (5.7 \pm 1.0) \cdot 10^{-4}\,\mathrm{fm}^3$ and $\alpha_\pi + \beta_\pi = 0.16 \cdot 10^{-4}\,\mathrm{fm}^3$. Because of the smallness of the pion-structure effects (less than 20%) radiative corrections of order α have to be included also in the analysis of pion-Compton scattering data. It is found that these QED radiative corrections [4] have the same kinematical signature as the polarizability difference $\alpha_\pi - \beta_\pi$, but their effects are suppressed in magnitude by about a factor 5 or more. The other topic of my talk is the description of the (charged and neutral) pion-pair photoproduction processes $\pi^-\gamma \to \pi^-\pi^0\pi^0$ and $\pi^-\gamma \to \pi^+\pi^-\pi^-$ at next-to-leading order in chiral perturbation theory [5]. Whereas the total cross section $\sigma_{\rm tot}(s)$ for the neutral channel $\pi^-\gamma \to \pi^-\pi^0\pi^0$ gets enhanced sizeably by the inclusion of chiral loop and counterterm corrections, the analogous effects turn out to be very small for the charged channel $\pi^-\gamma \to \pi^+\pi^-\pi^-$. This different behavior can be understood from the varying influence of the chiral corrections on the pion-pion final state interaction ($\pi^+\pi^- \to \pi^0\pi^0$ versus $\pi^-\pi^- \to \pi^-\pi^-$). The QED radiative corrections have also been calculated for the process $\pi^-\gamma \to \pi^-\pi^0\pi^0$ (simpler case) [5]. These affect the total cross section by at most 2%. The predictions of chiral perturbation theory for low-energy pion-photon reactions can be tested soon by the COMPASS experiment at CERN which uses Primakoff scattering of high-energy pions in the Coulomb-field of a heavy nucleus. A preliminary analysis for $\pi^-\gamma \to \pi^+\pi^-\pi^-$ in the energy region $3m_\pi < \sqrt{s} < 5m_\pi$ confirms the prediction of chiral perturbation theory.

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The nuclear force problem: Have we finally reached the end of the tunnel?

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In the past decade, there has been substantial progress in the derivation of nuclear forces from chiral effective field theory (EFT). Accurate two-nucleon forces have been constructed at next-to-next-to-next-to-leading order (N^3LO) and applied [together with three-nucleon forces (3NFs) at NNLO] to nuclear few- and many-body systems—with a good deal of success. This may suggest that the 80-year old nuclear force problem has finally been cracked. Not so! Some pretty basic issues are still unresolved. In this talk, we focus on the two most pressing ones [1], namely, sub-leading 3NFs and the proper renormalization of the two-nucleon potential.

Concerning **three-nucleon forces**, the bottom line is this:

- The chiral 3NF at NNLO is insufficient.
- The chiral 3NF at N^3LO (in the Δ-less theory) won't do it.
- However, sizable contributions are expected from one-loop 3NF diagrams at N^4LO of the Δ-less or N^3LO of the Δ-full theory. Thus, this is what needs to be attacked next.

Non-perturbative renormalization of the NN **potential.** Naively, the 'best' method of renormalization is the one where the momentum cutoff is taken to infinity while maintaining stable results. However, it has been shown for the chiral NN potential that this type of renormalization leads to a rather erratic scheme of power counting and does not allow for a systematic order-by-order improvement of the predictions. This should not come as a surprise, since the chiral EFT these potentials are based upon is designed for momenta below the chiral-symmetry breaking scale of about 1 GeV. Therefore, in the spirit of an investigation which Lepage conducted in 1997 for a toy model, we have examined the cutoff dependence of the predictions by the chiral NN potential at next-to-leading order (NLO) for phase shifts and NN observables using cutoffs below the hard scale *identifying extended areas of cutoff independence* ("plateaus").

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Three-nucleon forces with explicit Delta fields

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Description of light nuclei and low energy nuclear reactions can be given in a model-independent way by using chiral effective field theory (EFT) of QCD. In this framework nuclear forces are described by pion and nucleon (and possibly Δ) rather than fundamental quark-gluon degrees of freedom in harmony with the symmetries of QCD. In the two-nucleon sector, chiral nuclear forces have been studied up to next-to-next-to-next-to-leading order (N^3LO) in chiral expansion. All the proton-neutron phase-shifts upto $E_{\text{lab}} = 200\,\text{MeV}$ and deuteron observables are very well described at this order [1]. Three-nucleon forces have been analyzed up to next-to-next-to-leading order (N^2LO) in chiral expansion. While many observables like e.g. differential cross sections of nucleon-deuteron scattering at low energies are very well described at N^2LO there are some deficiencies in the description of vector analyzing power in neutron-deuteron elastic scattering at low energies, known in the literature as A_y-puzzle, and in the so called space-star configuration of nucleon-deuteron break up (see [1] for extensive discussion). This suggests to analyze the three-nucleon forces upto N^3LO.

Recently the expressions for long range part of N^3LO contributions to the three-nucleon forces have been worked out by our group [2] and partly by [3]. Their numerical implementations are still under development.

$\Delta(1232)$-resonance plays a special role in the nuclear physics. Its contributions to the nuclear forces are sizeable and are hidden in the unnaturally large low energy constants in the Δ-less chiral EFT. Taking Δ-resonance explicitly into account leads to a better convergence of the chiral expansion of nuclear forces [4]. Our current analysis of the N^3LO long-range contributions to the three-nucleon force shows sizeable effects coming from Δ-degrees of freedom. Sizable Δ-contributions to the three-nucleon force at N^3LO might potentially resolve the still existing puzzles in the three-nucleon sector. It remains to be seen if the numerical implementations of these and other N^3LO-contributions will lead to a better description of the experimental data.

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What have we learned about three-nucleon forces at intermediate energies?

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Three-body systems have been studied in detail at KVI and other laboratories around the world in the last few years. Two categories of reactions have been chosen to investigate these systems, namely elastic and break-up reactions in proton-deuteron scattering in which only hadrons are involved, and proton-deuteron capture reaction involving real and virtual photons in the final state.

Even though a relatively good understanding of most phenomena in nuclear physics has been arrived at by only considering two-nucleon forces, high precision three-nucleon data have revealed the shortcomings of these forces. Hadronic reactions in three-body systems excluding photons give a handle on effects such as those from three-body forces. In the last few decades, the two-nucleon system has been thoroughly investigated both experimentally and theoretically. These studies have resulted in modern potentials which describe the bulk of the data in a large range of energy. This knowledge can be employed in a Faddeev-like framework to calculate scattering observables in three-body systems. In regions and for the reactions in which the effects of Coulomb force are expected to be small or can be calculated accurately, and energies are low enough to avoid sizable relativistic effects, deviations from experimental data are a signature of three-body force effects.

At KVI, various combinations of high-precision cross sections, analyzing powers and spin-transfer coefficients have been measured at different incident proton or deuteron beam energies between 100 and 200 MeV for a large range of scattering angles and for the reactions mentioned above. Calculations based on two-body forces only do not describe the data sufficiently. The inclusion of three-body forces improves the discrepancies with data significantly. However, there are still clear deficiencies in the calculations.

The data from various laboratories have been combined to show globally how one can study the effects of three-body forces. It is very clear that the size of the effects generally increases with increasing the beam energy. The predictions of cross sections generally improve when three-nucleon forces are explicitly added in the calculations. The spin observables, on the other hand, show a mixed picture. For some observables, the predictions improve and for some other, they deviate even further from the data once the three-nucleon force is added.

With the wealth of the data now available for various reactions in the three-body systems, nuclear forces should be developed which can describe the data. The developments within effective field theories should also be vigorously pursued to be able to predict observables at higher energies.

Nuclear physics from lattice effective field theory

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Lattice effective field theory is a first principles method which combines the theoretical framework of effective field theory with supercomputer lattice simulations. Some recent developments in lattice effective field theory can be found in Ref. [1,2,3,4].

Our collaboration has recently completed lattice calculations of the low-energy spectrum of carbon-12 using effective field theory [5]. In addition to the ground state and excited spin-2 state, our calculations find a resonance at -85(3) MeV with all of the properties of the Hoyle state and in agreement with the experimentally observed energy. The Hoyle state plays a crucial role in the hydrogen burning of stars heavier than our sun and in the production of carbon and other elements necessary for life. This excited state of the carbon-12 nucleus was postulated by Hoyle [6] as a necessary ingredient for the fusion of three alpha particles to produce carbon at stellar temperatures. These lattice results provide insight into the structure of this unique state and new clues as to the amount of fine-tuning needed in nature for the production of carbon in stars.

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The hadronic vacuum polarisation contribution to $(g-2)_\mu$ from lattice QCD

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The anomalous magnetic moment of the muon, $a_\mu = \frac{1}{2}(g-2)_\mu$, provides one of the most stringent tests for physics beyond the Standard Model, thanks to the impressive precision which has been reached in its direct experimental measurement as well as in theoretical predictions [1]. The accuracy of the latter is limited by hadronic contributions, notably hadronic vacuum polarisation. We report on our efforts to evaluate this contribution, $a_\mu^{\rm had}$, using lattice simulations of QCD. The starting point is the convolution integral

$$a_\mu^{\rm had} = 4\pi^2 \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2\, f(Q^2)\{\Pi(Q^2) - \Pi(0)\}, \qquad (1)$$

where $\Pi(Q^2)$ is related to the vacuum polarisation tensor. Since $f(Q^2)$ is strongly peaked for momenta near m_μ, which is an order of magnitude smaller than what can conventionally be realised, lattice simulations cannot constrain the integral where it receives its dominant contribution. Furthermore, the Wick contractions for the vacuum polarisation tensor produce contributions from so-called quark-disconnected diagrams, which are notoriously difficult to compute with good statistical accuracy. Our calculation involves several novel ideas: using partially quenched ChPT, it was shown in [2] that connected and disconnected contributions can be evaluated separately. Furthermore, the latter can be shown to be suppressed by a factor 10. During the first stage of the project we therefore concentrate on the connected contribution, which is evaluated using twisted boundary conditions [3]. This shifts the minimum accessible value of Q into the peak region of the convolution function. Our preliminary results [4,5] indicate that our strategy leads to a significant improvement of the overall accuracy in lattice calculations of $a_\mu^{\rm had}$.

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Prediction of super-heavy N^* and Λ^* resonances with hidden charm and beauty

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The interaction between various charmed mesons and charmed baryons are studied within the framework of the coupled channel unitary approach with the local hidden gauge formalism [1]. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass around 4.3 GeV and width smaller than 100 MeV. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks and can be looked for at the forthcoming PANDA/FAIR experiments.

Then the same approach is extended to the hidden beauty sector [2]. A few narrow N^* and Λ^* around 11 GeV are predicted as dynamically generated states from the interactions of heavy beauty mesons and baryons. Production cross sections of these predicted resonances in pp and ep collisions are estimated as a guide for the possible experimental search at relevant facilities.

The S-wave $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states with isospin I=1/2 and spin S=1/2 are also dynamically investigated within the framework of a chiral constituent quark model by solving a resonating group method (RGM) equation by W.L.Wang et al. [3]. They confirm that the interaction between Σ_c and $\bar{D}$ is attractive and results in a $\Sigma_c\bar{D}$ bound state not far below threshold.

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A coherent view of the charmonium hadronic and radiative decays

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The open charm effects via intermediate hadron loop transitions seem to be essential for understanding some of those long-standing puzzles in charmonium decays into light hadrons. Some of those include the $\psi(3770)$ non-$D\bar{D}$ decays, and the so-called "$\rho\pi$ puzzle" which is about the abnormally small ratio of $Br(\psi' \to \rho\pi)/Br(J/\psi \to \rho\pi)$ in comparison with the pQCD expected "12%", namely, the "12% rule". We show by quantitative calculations that the intermediate charmed meson loops provide a correlative mechanism for the Okubo-Zweig-Iizuka (OZI) rule violations and helicity selection rule violations in charmonium decays into light hadrons [1,2,3,4]. Further possible evidences for the intermediate charmed meson loops in the isospin violating transitions between charmonium states [5,6], and radiative decays [7,8] are also discussed.

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Dressed Polyakov loop and the relation between chiral and deconfinement phase transitions

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The interplay between chiral restoration and deconfinement phase transition is very important for the QCD phase diagram at high temperature and density. Recently the proposed "quarkayonic" phase [1] raises much interests in discussing the possibility of chiral symmetric but confined phase structure. In the Polyakov-loop NJL model [2], the relation between the two phase transitions is much parameter dependent, the chiral restoration can happen earlier or latter than the deconfinement phase transition, also the two phase transitions can coincide with each other. We use the dressed Polyakov loop [3] as an equivalent order parameter of deconfinement phase transition, and investigate the chiral and deconfinement phase transitions. In Ref. [4] we find that in the case of first order and second order phase transitions, the chiral phase transition always coincide with deconfinement phase transition, and in the case of crossover, the chiral transition temperature is always smaller than that of the deconfinement. We also find that the phase transitions for light u, d quarks and s quark are sequentially happened. Our result at zero baryon density agrees with the lattice result from Wuppetal-Budapest group [5].

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Heavy Quarkonium in a weakly coupled Quark-Gluon Plasma

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Heavy quarkonium has been suggested since long ago [1] as a probe of the medium that forms in heavy-ion collision experiments. Recent efforts have focused on a systematic derivation of the heavy quark potential at finite temperature. To this end an Effective Field Theory (EFT) framework was constructed, based on the successful non-relativistic EFTs at $T = 0$ for heavy quarkonium [2]. This non-relativistic EFT study of quarkonium bound states in a plasma was initiated in [3] in the static limit, and in [4] for QED.
In this talk we report the main findings of [5], where this systematic and rigorous EFT approach is employed for the calculation of the heavy quarkonium spectrum and decay width in a QCD plasma, whose temperature T and screening mass $m_D \sim gT$ satisfy the hierarchy $m\alpha_s \gg T \gg m\alpha_s^2 \gg m_D$ (m being the heavy-quark mass, $m\alpha_s$ the typical momentum transfer and $m\alpha_s^2$ the binding energy). We first sequentially integrate out the scales m, $m\alpha_s$ and T and next we carry out the calculations in the resulting effective theory. We finally discuss the relevance of this hierarchy and the implications of our results concerning the behaviour of the ground states of bottomonium in heavy ion collisions.

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Some novel developments in quarkonium electromagnetic transitions

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Some recent theoretical developments in understanding quarkonium radiative transitions have been presented in this talk. 1). The recent BaBar experiment indicated that the $X(3872)$ charmonium state may carry the quantum number 2^{-+}, instead of the commonly assumed 1^{++}[1]. By assuming the X meson to be the canonical η_{c2} meson, we comprehensively investigate the spin-flipped radiative transitions $\eta_{c2} \to J/\psi(\psi') + \gamma$[2] by utilizing potential nonrelativistic QCD (pNRQCD) framework[3] and phenomenological potential models. We have considered the $^3S_1 -^3 D_1$ mixing effects in ψ' and identified all the three multipole amplitudes. Comparing our predictions with the existing B factory measurements, we tend to conclude that the assignment of the $X(3872)$ with the η_{c2} seems to be strongly disfavored.

2). The long-awaited bottomonium ground state $\eta_b(1S)$ has been recently discovered in hindered magnetic dipole transitions process $\Upsilon(3S) \to \eta_b + \gamma$[4]. In such a case, the emitted photon carries a rather large energy about 1 GeV, which casts some doubt on the applicability of the conventional long-wavelength approximation. By assigning the photon momentum as semi-hard ($k \sim \mathcal{O}(mv)$), where mv signifies the typical heavy quark 3-momentum inside quarkonium, we have developed a novel *hard-scattering* mechanism, to describe these kinds of strongly hindered radiative transitions[5]. The reasonable agreement with the BaBar measurement has been achieved.

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Electric properties of halo nuclei from EFT

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Our recent computation of the electromagnetic properties of single-neutron halo nuclei [1] uses "halo effective field theory" [2]. The expansion in halo EFT is in powers of $R_{\rm core}/R_{\rm halo}$, where $R_{\rm core}$ and $R_{\rm halo}$ are the range of the core-neutron interaction and the size of the bound state, respectively. Carbon-19 is one nucleus to which we apply our theory: it has a $1/2^+$ state which is predominantly a ^{18}C core with an (s-wave) orbiting neutron. In that case the Coulomb dissociation data of Ref. [3] are quite well described by an NLO computation in halo EFT. The $d\mathrm{B(E1)}/dE$ strength measured in such experiments has universal features.

The Beryllium-11 nucleus has more low-energy levels: there a shallow $1/2^+$ (s-wave) and $1/2^-$ (p-wave) state are present. At LO in halo EFT we have three parameters: the binding energies of these two states, as well as the effective "range" for p-wave ^{10}Be-n scattering. We use data on the two levels and the B(E1) strength of the transition between them to fix these parameters.

The $d\mathrm{B(E1)}/dE$ spectrum obtained from Coulomb excitation of ^{11}Be into ^{10}Be plus a neutron has been calculated and compared to experimental data [4]. At next-to-leading order (NLO) one additional parameter associated with the asymptotic normalization coefficient of the $1/2^+$ state can be adjusted to obtain a good description of the low-energy portion of this observable. The EFT's convergence pattern is as expected, given the nominal expansion parameter.

The resulting NLO prediction for the charge radius of the $1/2^+$ state is consistent with the experiment [5]. We also extracted the s-wave scattering length and effective range and the p-wave scattering volume that parametrize scattering of a neutron from ^{10}Be. Lastly, we find "universal" correlations between electromagnetic observables in halo nuclei with shallow $1/2^+$ and $1/2^-$ states.

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Electromagnetic Processes in Few-Nucleon Systems at Low Energy

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Nuclear potentials and electromagnetic currents derived in chiral effective field theory (χEFT) have been used recently to study magnetic moments and radiative captures of thermal neutrons on few-nucleon systems. In the present talk, we discuss the χEFT approach, specifically as it pertains to the construction of the electromagnetic current operator [1], and provide a critical review of results obtained so far for these processes [2]. In particular, we show that the predicted cross sections for the n-d and n-^{3}He captures—both are induced by $M1$ transitions, which are strongly inhibited at the one-body level—are well reproduced by theory.

We also address the issue of relativistic corrections to chiral potentials [3]. We sketch the methods used to construct the most general, relativistically invariant, contact Lagrangian at order Q^2, from which a complete, but non-minimal, set of (contact) interaction terms is obtained. In the non-relativistic limit, these consist of 2 leading independent operator combinations of order Q^0, accompanied by specific Q^2 corrections, and 7 sub-leading ones of order Q^2. We show that this result also follows by enforcing the commutation relations among the Poincaré group generators order by order in the low-energy expansion. These boost corrections should be taken into account in χEFT calculations of nuclei with mass number $A > 2$.

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The Power of χEFT: Connecting Nuclear structure and Weak Reactions

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The main success of χEFT is in supplying a perturbative microscopic Lagrangian applicable in the low energy nuclear regime. This Lagrangian is consistent with the symmetries of the fundamental theory, and in particular the approximate chiral symmetry. This Lagrangian is used to derive not only a nuclear potential, but also Noether currents, exploiting the global $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ chiral symmetry. As this is the gauging of the electro-weak interaction, this current is the scattering operator in electro-weak processes. This connection has a very useful result: an inherent connection between strong observables, dictated by the potential, and electro-weak processes. In fact, the same low-energy constants (LECs) appear in both the force and the current. Another advantage is that, up to $\mathcal{O}(Q)^3$, all LECs in the current, with the exception of one, can be fixed in pion-nucleon scattering. The extra LEC, coined $\hat{d}_R$, appears in a three-nucleon force term as well as in electro-weak two-body currents.

This connection has been used to fix the three-nucleon forces to high accuracy, facilitated by the accurate measurement of triton half-life [1,2]. In addition, using this relation corrects an unphysical trend of standard nuclear physics approach when applied to the beta-decay of ^{6}He [3].

An extension of this approach to electro-weak processes in medium-heavy nuclei can be found in [4]. There, normal ordering of the 2-body current is used to construct an effective single nucleon operator. This predicts a substantial effect on the rare $0\nu2\beta$ decay nuclear matrix element. In this application, χEFT supplies a consistent approach to extrapolate the current to the high momentum characteristic of these decay, from the low-energy regime of ordinary β- and $2\nu2\beta$-decays.

One can conclude that this is a most effective, pragmatic, and already successful application of χEFT. This approach is and can be used to predict, without free parameters, electro-weak, as well as strong, observables in nuclei.

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A high-accuracy calculation of the πd scattering length

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For many years a combined analysis of pionic hydrogen and deuterium atoms has been known as a good tool to extract information on the isovector and especially on the isoscalar S-wave πN scattering length [1]. However, given the smallness of the isoscalar scattering length, the analysis becomes useful only if the pion-deuteron scattering length is controlled theoretically to a high accuracy comparable to the experimental precision. To achieve the required few-percent accuracy one needs theoretical control over all isospin conserving 3-body $\pi NN \to \pi NN$ operators up to one order before the contribution of the dominant unknown $4N\pi\pi$ contact term. This term appears at next-to-next-to-leading order in Weinberg counting. The largest effect in the πd scattering length stems from the double-scattering process, with the pion scattered off two static (infinitely heavy) nucleons. Among the most relevant corrections are the triple-scattering term [2,3], the effect of nucleon recoil [4] related to the finite mass of the nucleon, dispersive corrections due to the processes $\pi d \to NN \to \pi d$ and $\pi d \to \gamma NN \to \pi d$, and the contribution which appears due to the treatment of the $\Delta(1232)$ resonance as an explicit degree of freedom [5]. In addition, one needs to include isospin violating (IV) effects in both two-body (πN) [6] and three-body operators. In Ref. [7] we accounted for virtual-photon effects and mass differences in the three-body operators. We also included all the isospin-conserving effects listed above. The resulting combined analysis of πH and πD atoms yields: $a^+ = (7.6 \pm 3.1) \cdot 10^{-3} M_\pi^{-1}$ and $a^- = (86.1 \pm 0.9) \cdot 10^{-3} M_\pi^{-1}$.

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Hyperon-nucleon and hyperon-hyperon interactions in chiral effective field theory

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With regard to the nucleon-nucleon (NN) system a description of high precision could be achieved within chiral effective field theory (EFT) [1,2]. Following the original suggestion of Steven Weinberg [3], in these works the power counting is applied to the NN potential rather than to the reaction amplitude. The latter is then obtained from solving a regularized Lippmann-Schwinger equation for the derived interaction potential. The NN potential contains pion-exchanges and a series of contact interactions with an increasing number of derivatives to parameterize the shorter ranged part of the NN force.

Recently, also baryon-baryon systems with strangeness were investigated within the framework of chiral EFT by the group in Jülich [4,5,6]. In these works the same scheme as applied in Ref. [2] to the NN interaction is adopted. Specifically, the interactions in the ΛN and ΣN channels [4] as well as those in the $S = -2$ sector ($\Lambda\Lambda$, $\Sigma\Sigma$, $\Lambda\Sigma$, ΞN) [5] were considered at leading order (LO). Moreover, predictions for the $S = -3$ and -4 baryon-baryon interactions were made [6], invoking constraints from SU(3) flavor symmetry. To LO in the power counting the baryon-baryon potentials involving strange baryons consist of four-baryon contact terms without derivatives and of one-pseudoscalar-meson exchanges, analogous to the NN potential [2].

It turned out that already at LO the bulk properties of the ΛN and ΣN systems can be reasonably well accounted for. Furthermore, the EFT results are consistent with the rudimentary empirical information available in the $S = -2$ sector. Preliminary but still incomplete results for the YN interaction to next-to-leading order look very promising too [7]. It will be interesting to see what can be achieved within a full calculation to NLO.

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Threshold resummation of heavy coloured-particle cross sections

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A precise theoretical description of the pair-production of heavy coloured particles is hampered by quantum corrections to the partonic cross sections of the form $\alpha_s^n \ln^m \beta$ and $(\alpha_s/\beta)^k$, which arise from soft-gluon emission and Coulomb exchange, respectively. Near the production threshold, defined by the limit $\beta \equiv \sqrt{1-4M^2/\hat{s}} \to 0$, such terms are parametrically enhanced, possibly leading to a breakdown of perturbation theory, and should ideally be resummed to all orders in the strong coupling α_s. In this talk I discuss how resummation of soft and Coulomb corrections can be achieved through an effective-theory description of the pair-production process, in which long-distance degrees of freedom with $q^2 \ll M^2$ are still dynamical, while the effect of *hard* modes with $q \sim M$ is encoded in the effective couplings of the low-energy theory. In [1] and [2], it has been shown that in such description the partonic cross section factorizes according to

$$\hat{\sigma} = \sum_S \sum_i H_i^S(\mu) \int d\omega \sum_{R_\alpha} J_{R_\alpha}^S(E-\omega/s) W_i^{R_\alpha}(\omega,\mu)\,, \tag{1}$$

where H_i^S, $J_{R_\alpha}^S$ and $W_i^{R_\alpha}$ are determined, respectively, by hard, Coulomb and soft modes only. In this approach, large logarithms of β are resummed to all orders by solving renormalization-group evolution equations for the functions H_i^S and $W_i^{R_\alpha}$, while resummation of Coulomb singularities, contained in $J_{R_\alpha}^S$, is obtained via techniques developed in the context of PNRQCD. The formalism has been recently applied to $t\bar{t}$ (Refs. [3], [4]) and to squark-antisquark production (Ref. [2]), where resummation effects on the total cross section were found to be sizeable, and thus relevant for phenomenological analysis at Tevatron and LHC.

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